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ELECTRICITY IN THE TERRESTRIAL ATMOSPHERE ABOVE THE EXCHANGE LAYER

by Elden C. Whipple, Jr.

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SUMMARY

Some of the reactions involving ions and electrons that might occur between the troposphere and the bottom of the ionospheric D-region (20 to 60 km) are discussed. Electrons are produced by cosmic ray ionization and by detachment from negative ions, and are lost by attachment to O_2. Photodetachment predominates during the day, but at night only collisional detachment is effective. Ion-ion recombination accounts for the removal of ions, the Thomson three-body process predominating below 45 km and the two-body mutual neutralization reaction above that altitude. Probable ion and electron densities in this region during quiet solar conditions are presented.

The mechanism of charge collection by bodies in the atmosphere is discussed with respect to two important applications: the effect of dust in providing a recombination surface for ions, and the problem of interpreting current-voltage curves obtained with ion probes. A perturbation solution of the Boltzmann equation to describe ion collection implies two assumptions, each of which becomes questionable at certain altitudes in this region of the atmosphere.

Direct measurements of the electrical properties of this region are difficult to perform from rockets because small currents must be measured accurately yet swiftly and without disturbing the local electrical environment seriously. The data obtained have proved difficult to interpret. Some new techniques are desirable, and possibilities are suggested.

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INTRODUCTION

At the Second International Conference on Atmospheric Electricity held at Portsmouth, New Hampshire, in 1958 only one paper was devoted to the electrical properties of the earth's atmosphere above balloon altitudes (Reference 1). Since then, a great amount of data has been obtained through rocket and satellite measurements of the electrical properties of the ionosphere above approximately 90 km. However, there has not been a corresponding advance in knowledge of the region between the altitudes accessible to balloons and the top of the D-region, that is, between about 30 and 90 km. The lack of attention to this part of the atmosphere has been due to several reasons. It naturally has been exciting to explore the properties of the exosphere and interplanetary space, and several scientists who attended the 1958 conference at Portsmouth have changed from studies of the troposphere to the investigation of the upper ionosphere. Another reason, however, for this gap has been the difficulty of making good measurements in this altitude region, which is too low for satellites and too high for balloons.

There have been theoretical advances in this period of time: Nicolet and Aikin (Reference 2) have discussed the mechanism of the D-region formation with respect to the relative importance of ultra-violet, x-ray, and cosmic radiation. Many of the rate coefficients for ion and electron reactions are better known now. Of particular importance here are the attachment and detachment coefficients for reactions of the type

$$e^- + M \rightleftharpoons M^- ,$$

where M is a neutral atom or molecule.

In the last two to three years there has been an increase in experimental efforts to understand the D-region, in particular, namely that part of the atmosphere below 90 km which can be ionized by solar radiation during quiet solar conditions. This report discusses the probable electrical properties of the atmosphere *below* the D-region, between approximately 20 and 60 km, during normal solar

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conditions when cosmic rays are the only source of ionization. Thus, the auroral latitudes where bremsstrahlung from auroral electrons can ionize down to approximately 30 km are not included in the discussion.

ION AND ELECTRON PROCESSES

In addition to the production of electrons by cosmic ray ionization, the following detachment processes from negative ions are potentially important for electron production at these altitudes.

Photodetachment:

$$O_2^- + h\nu \longrightarrow O_2 + e^- , \tag{1}$$

$$O^- + h\nu \longrightarrow O + e^- \tag{2}$$

with similar reactions for other negative ions.

Collisional detachment:

$$O_2^- + M \longrightarrow O_2 + M + e^- , \tag{3}$$

$$O^- + O \longrightarrow O_2 + e^- \tag{4}$$

and similar reactions for other negative ions.

Free electrons are lost mainly by attachment to O_2, although other reactions undoubtedly do occur:

$$O_2 + O_2 + e^- \longrightarrow O_2^- + O_2 , \tag{5}$$

$$O + e^- \longrightarrow O^- + h\nu , \tag{6}$$

$$O_3 + e^- \longrightarrow O_2^- + O . \tag{7}$$

Positive ions are lost by ion-ion recombination and also by recombination with electrons. The Thomson three-body ion-ion recombination process predominates below about 45 km; but at this altitude the two-body mutual neutralization reaction is equally efficient and, being pressure-independent, is predominant at higher altitudes. The coefficient for the latter reaction is between 10^{-8} and 10^{-7} cm^3/sec (Reference 3).

It is advantageous to use the ion equilibrium equation pertinent to clean air in the lower atmosphere to define a "reference" ion density profile denoted as n_0. Thus

$$n_0 = \left(\frac{q}{\alpha_1}\right)^{1/2} , \tag{8}$$

where q is the cosmic ray ionization rate and α_1 is the effective ion-ion recombination coefficient

$$\alpha_1 = \alpha_T + \alpha_M , \tag{9}$$

α_T being the Thomson three-body recombination coefficient and α_M the mutual neutralization coefficient. Physically this concept of n_0 is helpful because the presence of free electrons can be considered as a perturbation affecting the ion density profile. In the absence of free electrons, the positive and negative ion densities n_+ and n_- would revert to n_0 in clean air.

Reactions 1 through 7 have been discussed, along with other reactions, by authors interested in D-region ion and electron densities (References 2, 4, and 5 among others). Rate coefficients are available for Reactions 1 through 6 and are given in Table 1 with their sources.

Table 1

Rate Coefficients for Reactions 1 Through 6.

Coefficient	Value	Reference
Electron-ion recombination coefficient α_2	6×10^{-7} cm^3/sec (N_2^+)	6
	4×10^{-7} cm^3/sec (O_2^+)	Aikin, personal communication (1962)
	3×10^{-8} cm^3/sec (NO^+)	7
Mutual neutralization coefficient α_M	1×10^{-8} cm^3/sec	3
Photodetachment coefficient d	0.44/sec (O_2^-)	8
	1.4/sec (O^-)	2
Collisional detachment coefficient c	4×10^{-20} cm^3/sec (with O_2)	9
	1×10^{-14} cm^3/sec (with O)	4 and 5
Attachment coefficient a	1.5×10^{-30} cm^6/sec (three-body collision with O_2)	10
	1.3×10^{-15} cm^3/sec (radiative attachment to O)	11

Figure 1 compares the most probable electron production processes. The negative ion density was assumed to be equal to n_0 for the purpose of computing the curves indicating detachment processes. The values of q used here are those from Reference 12, corresponding to 41 degrees north geomagnetic latitude. It is evident that photodetachment predominates during the day if the negative ions are O_2^- or O^-. At night, collisional detachment and cosmic ray ionization both must be taken into account. However, only the collisional detachment process, Reaction 3, needs to be considered at night because the atomic oxygen rapidly combines with O_2 to form ozone (Reference 13).

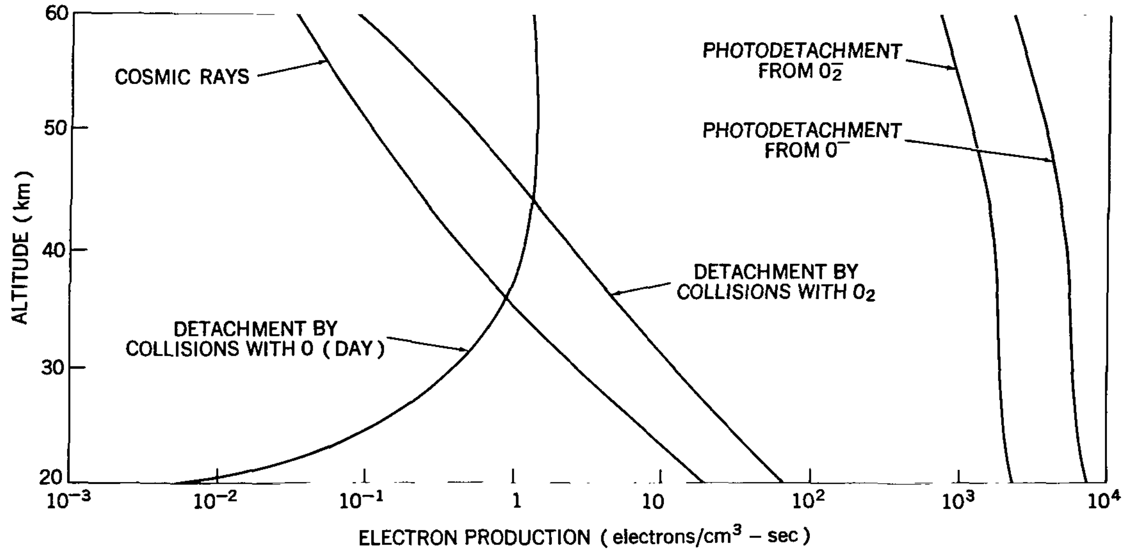

Figure 1—Rate of electron production for various processes.

Reaction 5, three-body attachment to molecular oxygen, undoubtedly predominates over the faster atomic oxygen attachment Reaction 6 as the most important electron loss process below 60 km because of the low atomic to molecular oxygen ratio. Whitten and Poppoff (Reference 5) have concluded that the latter reaction predominates only above 85 km. Electron-ion recombination occurs at a rate that is at least three orders of magnitude smaller than the rate for attachment to O_2 between 20 and 60 km if a recombination coefficient of 6×10^{-7} cm^3/sec (Reference 6) and an ion density of $10^4/cm^3$ are assumed–both quite generous assumptions.

The electron density during the day will depend on whether O_2^-, O^-, or some other negative ion is predominant. For O^- to be present in significant quantities, it must be formed by the charge exchange process:

$$O_2^- + O \longrightarrow O^- + O_2 \; ; \tag{10}$$

and the rate coefficient must be on the order of 10^{-10} cm^3/sec. This coefficient, although not known, may be as large as this, in which case O^- may be important during the day. However, this disagrees with the sunrise-sunset effect in the D-region (Reference 5).

Loss rates for negative ions are compared in Figure 2, where the reciprocal of the ion lifetime for various processes is plotted against altitude. It is clear that photodetachment is the only process that needs to be considered in the day if the ion is O_2^- or O^-. At night, both collisional detachment and recombination with positive ions must be taken into account although the former is not an efficient loss mechanism because of the rapid reattachment of the electrons to O_2. There is some question as to how much the detachment coefficients of Table 1 change when the reduced solar spectrum at lower altitudes is used, rather than that above the atmosphere. The cross sections for detachment from

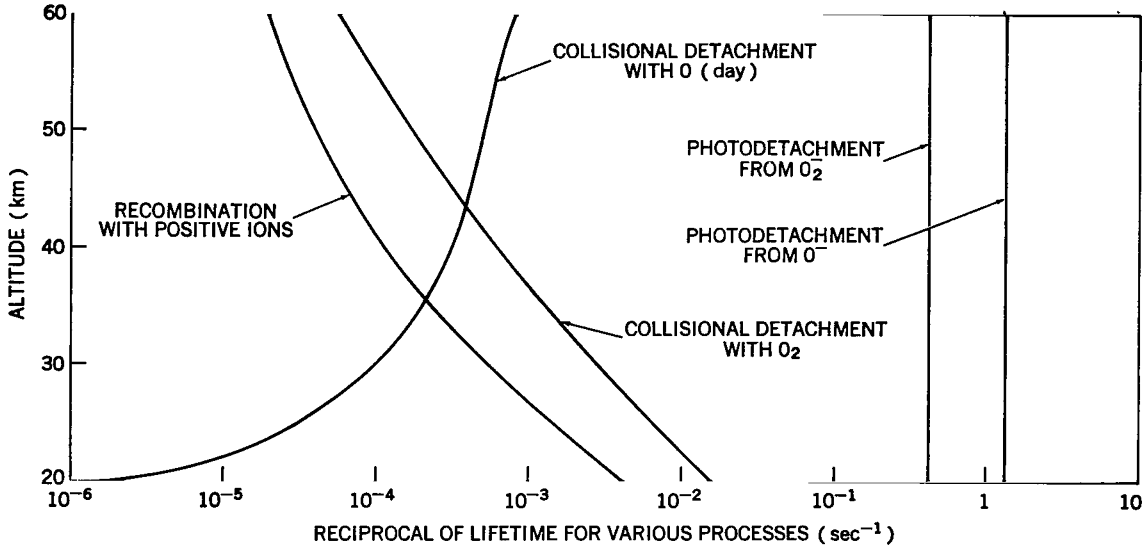

Figure 2—Rate of negative ion loss for various processes, $(1/n_-)(dn_-/dt)$.

O_2^- and O^- are almost entirely in the visible and infrared, implying little effect of the ultraviolet absorption by ozone on the coefficients. This again disagrees with the "sunrise" effect, and Whitten and Poppoff (Reference 5) have speculated that the O_2^- ion may be in a lower state in the atmosphere than during the experimental determination of the coefficient so that radiation between 2500 and 3000A is responsible for detachment in the atmosphere.

It is felt that the most likely negative ion is O_2^-. An upper limit on the electron density can be obtained by assuming O^- instead of O_2^-. The values of electron density obtained for these negative ion assumptions are compared in Figure 3, along with a maximum nighttime value. Other species of negative ions (O_3^-, NO_2^-, etc.) may occur, but more information on the rate coefficients involved in their production is needed before anything definite can be said about their importance. These have lower photodetachment coefficients and should yield lower daytime electron density values. Electron densities were computed for positive ion choices of N_2^+ and NO^+ so that the effect of different electron-ion recombination coefficients could be seen. Intermediate values of electron density would be obtained if the positive ion were O_2^+.

Positive ion densities, computed for the same choices of positive and negative ion species, are presented in Figure 4. The following equilibrium equations were used:

for positive ions,

$$q = \alpha_1 n_+ n_- + \alpha_2 n_+ n_e \text{ (day or night);} \tag{11}$$

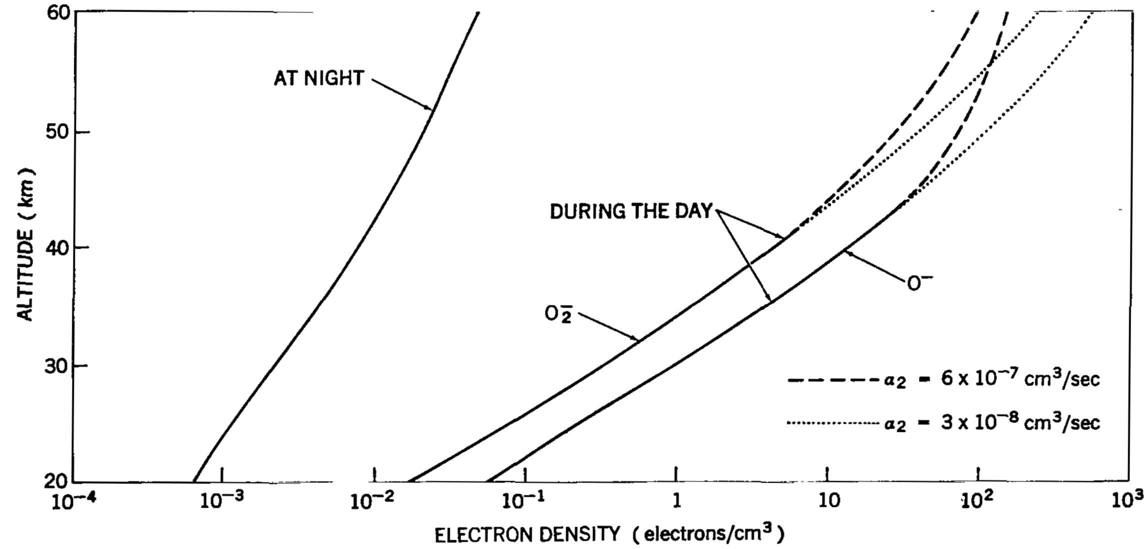

Figure 3—Electron densities resulting from various choices for positive and negative ion species.

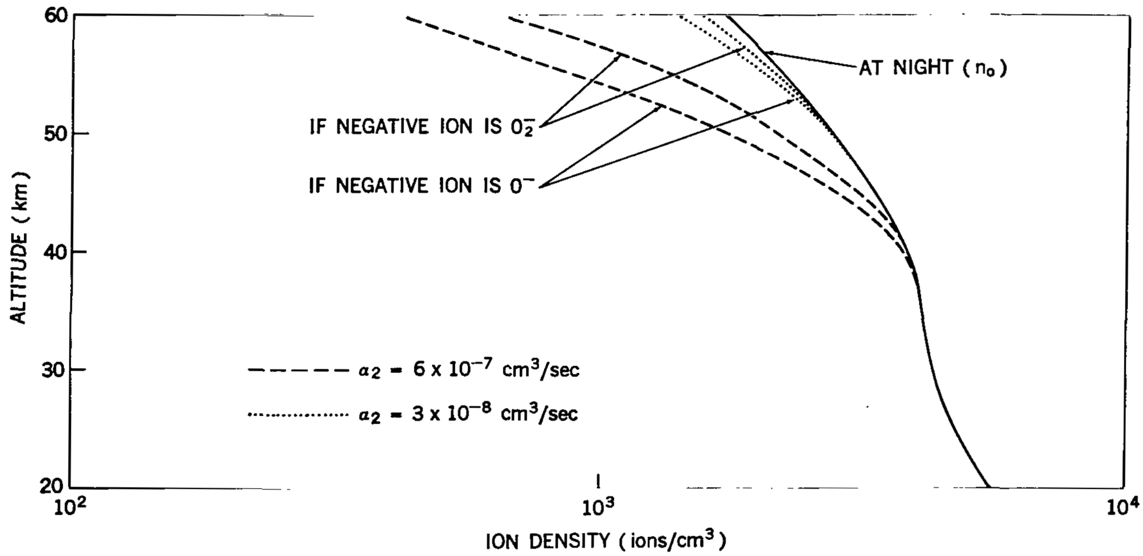

Figure 4—Positive ion densities resulting from various choices for positive and negative ion species.

for electrons (N being the number of O_2 molecules/cm³),

$$q + dn_- = aN^2 n_e + \alpha_2 n_+ n_e \quad \text{(day)} \, , \tag{12}$$

$$q + cn_- N = aN^2 n_e + \alpha_2 n_+ n_e \quad \text{(night)} \, ; \tag{13}$$

for negative ions,

$$aN^2 n_e = dn_- + \alpha_1 n_+ n_- \quad \text{(day)}, \tag{14}$$

$$aN^2 n_e = cn_- N + \alpha_1 n_+ n_- \quad \text{(night)}; \tag{15}$$

and the neutrality equation,

$$n_+ = n_e + n_- \ . \tag{16}$$

Solutions obtained during the day are

$$\left.\begin{aligned} n_+ &\approx \sqrt{\frac{q}{\alpha_1}} \sqrt{1 + \frac{d(\alpha_1 - \alpha_2)}{aN^2 \alpha_1 + d\alpha_2}} \\ n_e &\approx \frac{q + dn_+}{aN^2 + d} \end{aligned}\right\} \tag{17}$$

and those obtained at night are

$$\left.\begin{aligned} n_+ &\approx \sqrt{\frac{q}{\alpha_1}} \sqrt{\frac{aN^2 \alpha_1 + cN\alpha_1}{aN^2 \alpha_1 + cN\alpha_2}} \rightarrow \sqrt{\frac{q}{\alpha_1}} \\ n_e &\approx \frac{q + cNn_+}{aN^2 + cN} \rightarrow \frac{q + cNn_+}{aN^2} \end{aligned}\right\} \tag{18}$$

During the day the electron density is essentially proportional to the appropriate negative ion photodetachment coefficient. Above 45 km it is mildly sensitive to the nature of the positive ion. If the negative ion were not O_2^- or O^- but something with a low photodetachment coefficient, then the electron density would approach the negligible nighttime values.

The positive ion density is sensitive to the nature of the ion only at altitudes where recombination with electrons can compete with ion-ion recombination. Hence the density profile corresponding to the choice of N_2^+ and O^- represents a sort of lower limit to the ion density at this latitude unless the true electron-ion recombination coefficient is even higher than 6×10^{-7} cm^3/sec.

Nicolet and Aikin (Reference 2) have obtained electron and ion densities for the D-region above 60 km under quiet solar conditions. Their values at 60 km fall within the range of values obtained here for the same altitude.

In the lower atmosphere, ions form clusters with neutral molecules so that the effective ion mass is larger than that of the simple molecular ion. This tendency to cluster would lower the value of the effective recombination coefficient. The altitude at which clustering may become significant is not known, but it could perhaps be detected by measuring the ion density at night. An abrupt decrease with height in the ion density at a certain altitude might be indicative of the increase in the value of the recombination coefficient corresponding to cluster disassociation.

These considerations all have been for a clean atmosphere where the diffusion of electrons and ions to dust is negligible. Before considering this effect on the electron and ion densities, the mechanism of charge collection by bodies in this part of the atmosphere will be discussed.

CHARGE COLLECTION BY BODIES IN THE ATMOSPHERE

The theory of charge collection by bodies in the atmosphere has two important applications: One is the role that dust plays in the ion equilibrium in the atmosphere by providing a recombination surface; the other is in the use of probes where a current-voltage characteristic is interpreted in terms of the atmospheric electrical properties.

The atmosphere up through the D-region can be divided into two distinct regions as far as this problem is concerned: (1) lower altitudes where the ionic mean free path L is much smaller than the body dimension, and (2) higher altitudes where this is no longer true. The two cases where L is either much larger or much smaller than the body dimension have been treated extensively in the literature; but this is not true for the transition region, where L is the same order of magnitude as the collecting body. The transition region occurs at different altitudes for the two applications of concern here because of the difference in size between dust particles and probes. A typical probe is much larger than the mean free path to about 70 km, where L is about 0.1 cm. On the other hand, the transition altitude for a 10-micron dust particle occurs at 35 km.

Combination coefficients for the diffusion of ions to dust in the lower atmosphere have been obtained by Gunn (Reference 14) and Bricard (Reference 15, and a personal communication from Bricard in 1963). Use of probes in the lower atmosphere is also well understood (References 16, 17, 18, and 19 among others). All of these applications have been treated in essentially the same way—by considering the current density $\vec{J}$ to consist of separate terms corresponding to conduction, diffusion, and perhaps convection. The total current to the body in question is obtained by expressing $\vec{J}$ in terms of the local field quantities (electric field, particle concentration and its gradient, airflow, etc.) and integrating over the appropriate collecting area. Space charge effects can be taken into account through Poisson's equation.

The use of the current density in terms of transport coefficients is given by

$$\vec{J} = \sigma\vec{E} - eD\vec{\nabla}n + ne\vec{W} , \tag{19}$$

where σ is the conductivity, $\vec{E}$ the electric field, e the unit charge, D the diffusion coefficient, and $\vec{W}$ a convection velocity. The use of Equation 19 implies at least two assumptions, both of which can become questionable at certain altitudes in the atmosphere. This can be made clear by considering how this description of $\vec{J}$ is obtained. Boltzmann's equation in the steady state for the particle velocity distribution $f(\vec{v})$ is solved by assuming a solution of the form $f = f_0 + f_1$ and replacing the collision term by either the proper collision integral or the approximation $-(f - f_0)/\tau$, where f_0 is the normal Maxwell distribution and τ is an appropriate relaxation time. The quantity f_1 is assumed to be small so that its derivatives and powers can be neglected. Thus, for example, in a one-dimensional case where an electric field is the only external force we obtain

$$f_1 = f_0 - \tau \left(v_x \frac{\partial f_0}{\partial x} + \frac{eE}{m} \frac{\partial f_0}{\partial v_x} \right) , \tag{20}$$

where $\partial f_1/\partial x$ and $\partial f_1/\partial v_x$ have been neglected. The current density $\vec{J}$ is then obtained by integrating over the velocity distribution:

$$\vec{J} = e \int \vec{v} \, f(\vec{v}) \, d\vec{v} \quad . \tag{21}$$

If f_0 is assumed proportional to $n(x) \exp\left[- v_x^2/(2kT/m)\right]$, the conditions

$$\frac{\partial f_1}{\partial x} << \frac{\partial f_0}{\partial x} \text{ and } \frac{\partial f_1}{\partial v_x} << \frac{\partial f_0}{\partial v_x} \tag{22}$$

become

$$eEL << kT \text{ and } \frac{1}{n} \frac{\partial n}{\partial x} << \frac{1}{L} \quad . \tag{23}$$

That is, (1) the energy gained in one mean free path by an ion in an electric field must be less than its kinetic energy; and (2) the ion density must not change appreciably over one mean free path.

Consider now a typical probe such as a Gerdien condenser designed for a rocket-borne experiment. Let the maximum electric field in the condenser be about 5 volts/cm. For the first condition to be satisfied,

$$L << kT/eE \approx \frac{0.025 \text{ volt}}{5 \text{ volts/cm}} = 0.005 \text{ cm.}$$

The mean free path is less than this only below 45 km.

The second condition is not violated as easily in the lower atmosphere. However, during events such as solar flares there will be abnormal ionization in and below the D-region which could be large enough so that space charge sheaths may be formed around probes. In such a case, the ion density will change significantly over a Debye length. For example, during a strong solar flare the ion density at 75 km could be as high as $2 \times 10^4/\text{cm}^3$ (Reference 2). The corresponding Debye length is about 1 cm, which is only five times the mean free path at that altitude. Consequently, care should be used in interpreting probe data under such conditions.

The current to a charged sphere at rest in that part of the atmosphere where the mean free path is very large compared with the particle radius was first obtained by Mott-Smith and Langmuir

(Reference 20). Their solution for charges that are attracted is appropriate to the case where the particle radius is much smaller than the Debye length—the so-called orbital-motion-limited current case (Reference 21). The currents are

$$I_\pm = \pm \pi r^2 e C_\pm N_\pm \left(1 \mp \frac{\Phi e}{kT}\right) \text{ (attracted charges)} \tag{24}$$

and

$$I_\pm = \pm \pi r^2 e C_\pm N_\pm e^{\mp \Phi e/kT} \text{ (repelled charges),} \tag{25}$$

where r is the particle radius, $C_\pm$ the mean thermal velocity of the charged particle, and Φ the potential of the particle with respect to the atmosphere. The corresponding combination coefficients are

$$\beta_1 = \pi r^2 C_\pm \left(1 \mp \frac{\Phi e}{kT}\right) \text{ (attracted charges),} \tag{26}$$

$$\beta_2 = \pi r^2 C_\pm e^{\mp \Phi e/kT} \text{ (repelled charges).} \tag{27}$$

The combination coefficients obtained in the lower atmosphere by Gunn (Reference 14) and Bricard (private communication) are expressed as functions of the mean free path, and we would expect that in the limit, as the mean free path becomes very large, these would approach the expressions appropriate in the upper atmosphere (Equations 26 and 27). However, this is true only for the case when the particles have zero charge on them. Examination of the derivation of the coefficients for the lower atmosphere shows that the boundary condition used at the particle surface can be improved. For example, Gunn (Reference 14) equates the current collected by the particle to the effusion current at a surface situated one mean free path from the particle surface. These effusion currents are identical to the currents given in Equations 24 and 25 for the case of zero charge. When we use the full expressions, Equations 24 and 25, for the boundary conditions and replace Φ by $\Delta\Phi$, the potential drop between the particle and the imaginary surface at one mean free path, we obtain the following combination coefficients that have the correct limit as $L \to \infty$ and can be used in the transition region in the atmosphere where $L \approx r$:

$$\beta_1 = \frac{\pi r^2 C_\pm \left(1 \mp \frac{Qe}{kTr} \pm \frac{Qe}{kT(r+\Delta)}\right) e^{\mp \frac{Qe}{kT(r+\Delta)}}}{1 \pm \frac{r^2 C_\pm}{4QU_\pm}\left[1 - e^{\mp \frac{eQ}{kT(r+\Delta)}}\right]} \tag{28}$$

and

$$\beta_2 = \frac{\pi r^2 C_\pm e^{\mp \frac{Qe}{kTr}}}{1 \pm \frac{r^2 C_\pm}{4QU_\pm}\left[1 - e^{\mp \frac{eQ}{kT(r+\Delta)}}\right]}, \tag{29}$$

where $Q = \Phi r$ is the charge on the particle of radius r, U is the ion mobility, and Δ is the corrected mean free path (Reference 22). The coefficients β_0, β_1, and β_2, where β_0 is the combination coefficient for zero charge on a particle, are plotted against altitude in Figure 5. The charge Q has been chosen so that $(\Phi e/kT) = \pm 1$ for β_1 and β_2 respectively.

The effect of dust in reducing the daytime ion density is shown in Table 2, where values of ion and electron density at 60 km in clean air are compared with the values obtained when a dust density of 1 particle/cm³ is assumed. To obtain these values, Equations 11, 12, and 14 were modified by adding a term corresponding to the diffusion to dust process. An additional equation was obtained by setting the net current to a dust particle equal to zero. Finally, Equation 16 had a term added corresponding to the charge per cm³ residing on dust particles. The effect of photoemission from the dust particles in sunlight in increasing the electron production rate has been neglected.

Table 2

Effects of One Dust Particle/cm³ on Ion and Electron Densities.

	No Dust	$r = 10^{-5}$ cm	$r = 10^{-4}$ cm	$r = 10^{-3}$ cm
n_+	625	466	15	0.271
n_-	544	403	0.8	8×10^{-3}
n_e	81	60	0.1	1×10^{-3}
Q/e	-	-3	-14.1	-0.262

*α_2 has been assumed to be 6×10^{-7} cm³/sec.

The problem of measuring conductivity with ion probes on a rocket has been discussed by Bourdeau, Whipple, and Clark (Reference 12) and by Smith (personal communication, 1963). Smith gives expressions for the current to a probe flush with the rocket skin, taking into account the fact that the measurement actually involves a double probe since the rocket body, as well as the

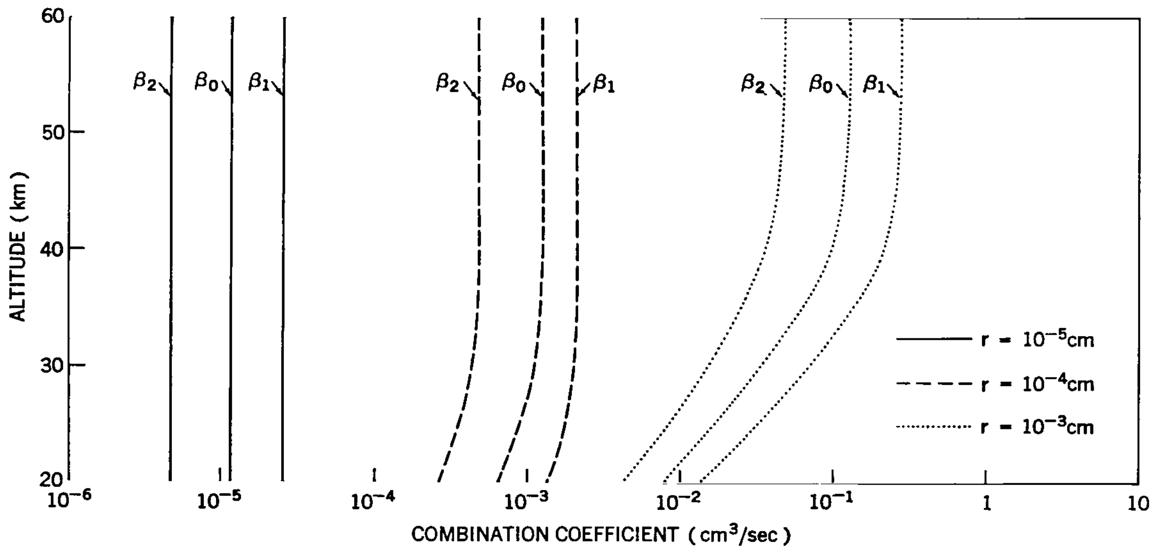

Figure 5—Combination coefficients for loss of ions to dust.

probe itself, collects current. It is not clear how this probe behaves in the transition region where the mean free path is large.

As an example of the kind of problem encountered in trying to predict the current-voltage characteristics of a probe in this region of the atmosphere and also as an indication of how the problem might be attacked, consider a hypothetical probe that combines the features of a Gerdien condenser and an ion trap, as shown in Figure 6. The probe consists of a hollow cylinder like a Gerdien condenser mounted so that there is an airflow of known velocity V entering the aperture as shown. A wire grid through which the air must flow is mounted at the aperture and is at the same potential as the outside of the probe, which we will assume to be the potential of the surrounding atmosphere. Inside the probe there is some means of collecting ions of the desired polarity so that none leave the cylinder with the air escaping from the other end. The ion collection mechanism is such that inside the cylinder there is a uniform attractive electric field at the aperture grid normal to the plane of the grid.

The measured ion current corresponds to what is usually called the *saturation current*; that is, it is determined by the rate at which ions enter the cylinder. In the lower atmosphere when the electric field is small, this current is given by

$$I = neVA , \tag{30}$$

where A is the cross-sectional area of this aperture.

Now it is well known that an ion trap mounted on the forward face of a satellite measures an ion current that is given by the identical expression (Reference 23). In spite of the vast difference in the mean free path in these two applications the current is of the same form because the same physical requirement is met, namely, that the net distance traveled by the ion in a given time with respect to

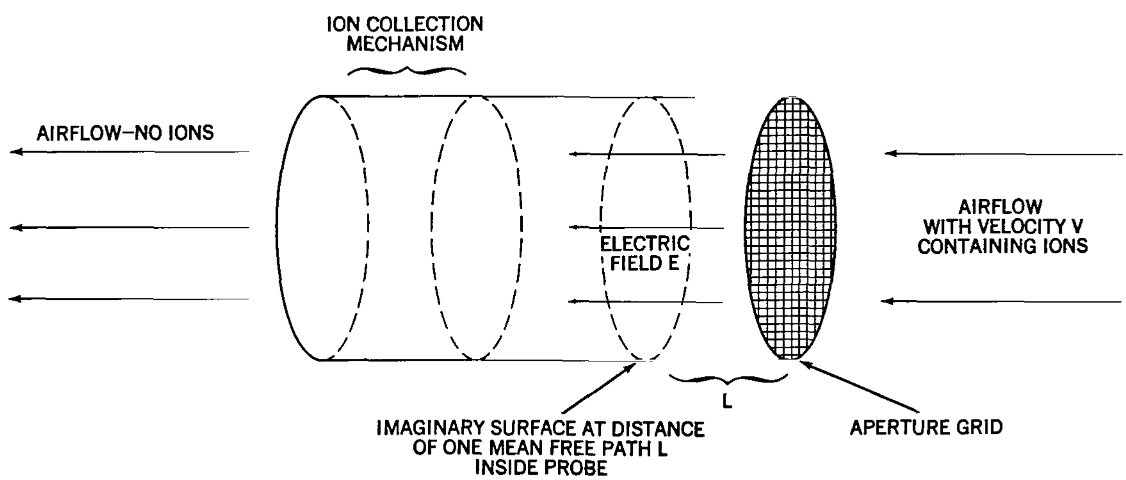

Figure 6—Hypothetical probe for collecting ions.

the medium is very small compared with the distance the ion is carried along by the medium in the same time. In the satellite case this is true because the satellite velocity is much greater than the random thermal velocity of the ion. In the lower atmosphere this is true because the short mean free path restricts the net distance that the ion travels even though the thermal velocity may be much greater than the airflow velocity.

The fact that Equation 30 is obtained in the satellite case by integrating Equation 21 suggests that it should be possible to obtain it in the same way for the other case, and hence for intermediate cases as well. This is indeed true if we are careful to take into account the ions that penetrate the grid once but then suffer a collision so that they are deflected back through the grid to escape. The following treatment indicates in a heuristic way how this might be done.

We assume that the ion velocity distribution at the aperture is Maxwellian except for the stream velocity. Thus,

$$f_1(v_x) = \frac{n}{2a\sqrt{\pi}} e^{-(v_x+V)^2/a^2} , \tag{31}$$

where a is the most probable ion thermal velocity. After the ions enter the grid, they are accelerated by the electric field; but because of collisions the net result is that the ions acquire a drift velocity w superimposed on the thermal and stream velocities. The resulting distribution is given by

$$f_2(v_x) = \frac{n}{2a\sqrt{\pi}} e^{-(V_x+V+w)^2/a^2} . \tag{32}$$

We now further assume that Equation 32 is descriptive of the distribution after the ions have suffered only one collision. In particular, $f_2(v_x)$ is taken to describe the distribution at a distance of one mean free path inside the cylinder from the aperture grid.

The initial current I_1 that enters the cylinder is given by Equation 21 integrated over $f_1(v_x)$:

$$I_1 = neVA\left[\frac{1}{2} + \frac{1}{2}\operatorname{erf}\frac{V}{a} + \frac{a}{2V\sqrt{\pi}} e^{-(V/a)^2}\right] . \tag{33}$$

The return current I_2, consisting of those ions that escape, is computed by determining the reverse current at the imaginary surface situated one mean free path inside the cylinder, taking into account the fact that not all the ions will have sufficient energy to overcome the potential rise from this surface to the grid. Thus,

$$I_2 = Ae\int_{-\infty}^{-v_2} v_x f_2(v_x)\, dv_x , \tag{34}$$

where v_2 is given by

$$v_2 = \sqrt{\frac{2eEL}{m}} \quad . \tag{35}$$

The result is

$$I_2 = -\,neA\,(V+w)\left[\frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\,x - \frac{a}{2\sqrt{\pi}\,(V+w)}\,e^{-x^2}\right] , \tag{36}$$

where

$$x = -\frac{1}{a}\left(V + w + v_2\right) \quad . \tag{37}$$

Hence, the desired current is given by the difference

$$I = I_1 - I_2 \quad . \tag{38}$$

This current normalized to the value given by Equation 30 is plotted against the mean free path parameter $2EeL/ma^2$ in Figure 7 for various values of V/a. The drift velocity w has been taken from Wannier's

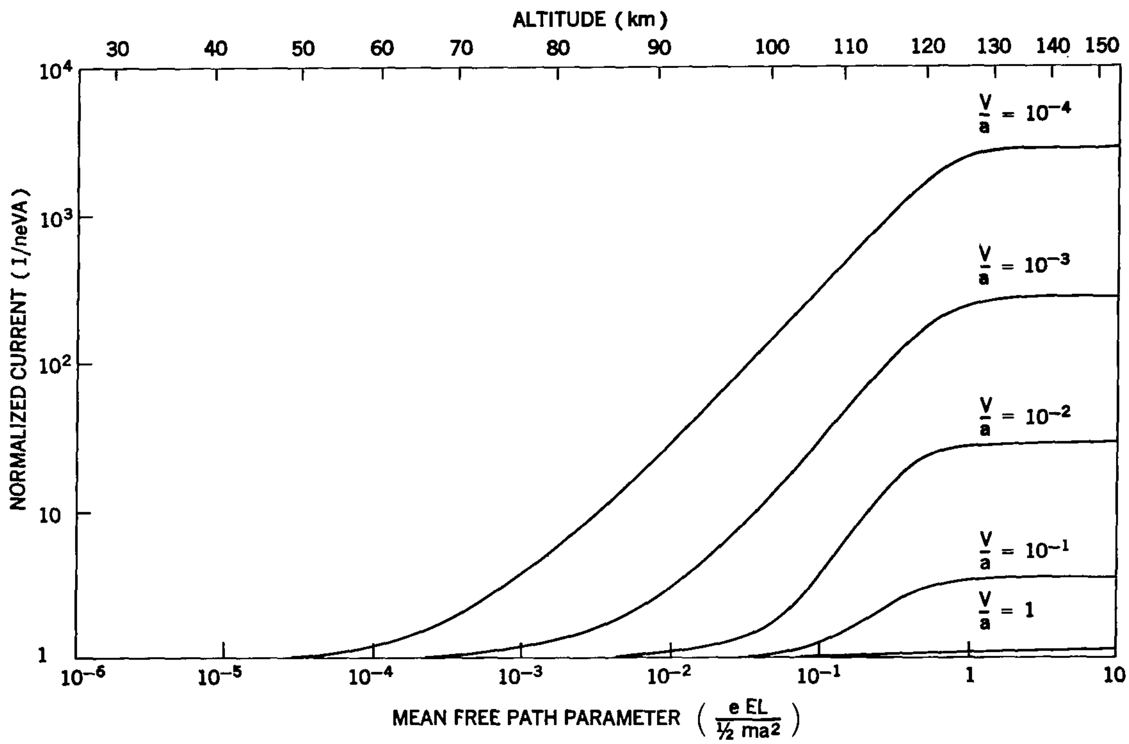

Figure 7—Ion current collected by the probe of Figure 6.

(Reference 24) equations with the assumption that the ion mass is equal to that of the neutral molecule. The corresponding altitude for a typical field of 1 volt/cm and a temperature of 300°K is also indicated. It is apparent that, as long as the stream velocity—i.e., the rocket or satellite velocity—is greater than the most probable ion velocity, then the collected current is independent of the altitude and is given by Equation 30. This is true for ion collection but not for electron collection from both rockets and satellites. For electrons, the deviation from Equation 30 is significant above 80 km for a rocket moving at 1 km/sec. It should be noted that, in addition to the neglect of any expected vehicle potential, this treatment neglects the entrance of particles at the exit end of the cylinder against the airstream.

EXPERIMENTAL PROBLEMS

It has not yet been possible to test experimentally the ideas presented in the first section as to the ion and electron densities in this part of the atmosphere above balloon altitudes. The results of only two measurements have been published so far (Reference 12 and a personal communication from Smith, 1963), and the interpretation of these measurements can be questioned. It is felt that the greatest need at present is the development of reliable measuring techniques. This means either that the same quantity should be measured simultaneously in different ways or that enough simultaneous measurements of different quantities should be made so that some independent requirement such as the neutrality equation can be used to verify the results.

To illustrate further some of the difficulties of data interpretation, some previously unpublished results are presented in Figures 8 and 9. Figure 8 shows positive and negative ion densities measured with two independent Gerdien condensers on an Aerobee rocket in Fort Churchill, Canada. The condensers had a constant potential of approximately ± 100 volts applied between the electrodes. The corresponding critical mobility for the condensers was computed to be equal to the actual small-ion mobility at 29 km (94.5 cm^2/volt-sec). Below this altitude, the measured currents that increased with altitude were assumed to be proportional to the ionic conductivity, and the ion density shown was computed by assuming a mobility corresponding to small ions. Above 29 km the measured current decreased, and the ion densities were computed by assuming the current to be proportional to the ion density and the volume airflow through the condenser. There is a discrepancy of about a factor of 2 in the ion densities obtained by the two methods at the critical altitude of 29 km. This may be due to the shock wave in front of the rocket, which would reduce the airflow through the condenser. However, this effect does not appear adequate to explain the continued decrease in current with altitude, since the rocket is decelerating in this region. At first glance it appears unreasonable that the ion density should decrease to such low values. However, the instrumentation performed properly, since the data obtained during the rocket descent reproduced that obtained on the ascent. The same phenomenon was also observed four days earlier on a similar rocket fired at night. A dust density of about one 1-micron particle/cm^3 is adequate above 30 km to account for the observed decrease in ion density. On the other hand, this effect may be due to uncertainties in how to interpret the behavior of the Gerdien condenser.

In contrast to this, the measurements between 23 and 29 km indicate relatively clean air. The negative-to-positive-ion conductivity ratio, which fluctuated irregularly from 0.61 to 1.37 between 15

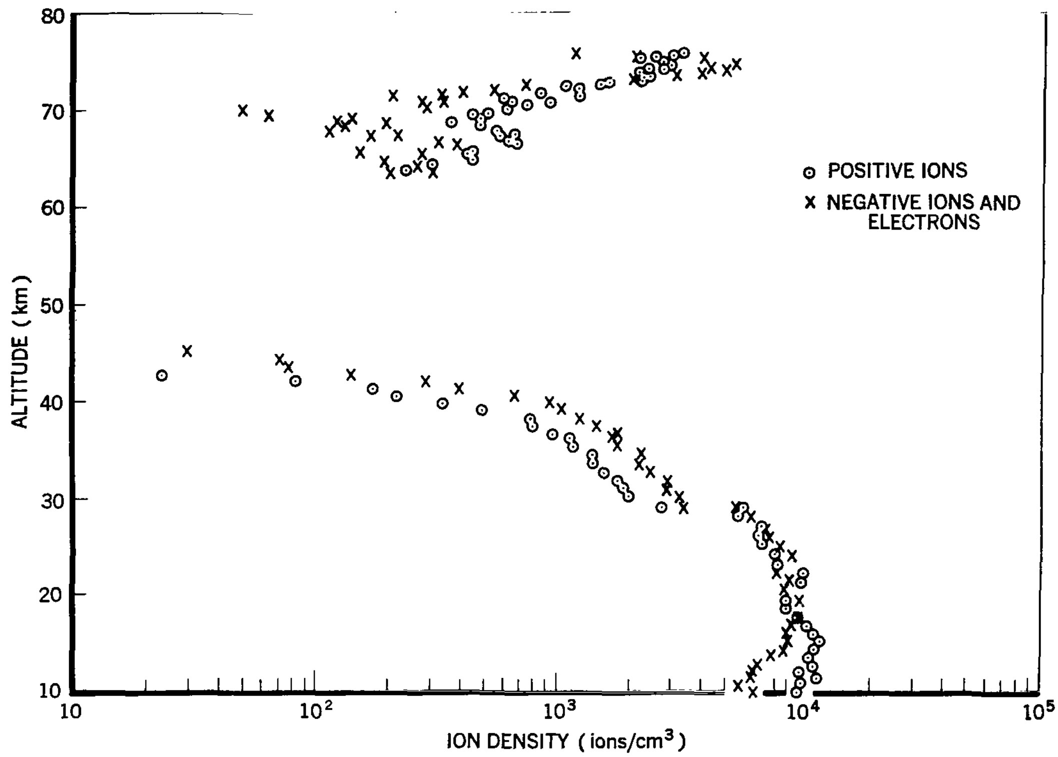

Figure 8—Charged particle densities at Fort Churchill, Canada. NASA rocket 1-02, 1150 CST, 27 November 1960 (ascent).

and 22 km with an average of 1.07, increased noticeably at 23 km and averaged 1.40 (approximately the small-ion mobility ratio) between 23 and 29 km.

Figure 9 shows positive ion and electron densities obtained from a Nike-Cajun rocket at Wallops Island, Virginia, in December 1961. The ion densities were obtained by the author from the measured conductivity using the probe described by Smith (personal communication, 1963), and are quite sensitive to the assumed ion mobility. Here Dalgarno's (Reference 25) estimate of mobility for N_2^+ in air was used. Electron densities were computed from measurements of the differential absorption of the ordinary and extraordinary propagation modes of a 3-Mc signal transmitted from the ground to the rocket (J. Troim, personal communication, 1962). The altitude-dependence of the electron collision frequency that is necessary for the computation is that given by Kane (Reference 26). There is only general agreement within an order of magnitude between the ion and electron results between 72 and 83 km—which is all that should be expected, considering the error bars on the electron density measurement and the uncertainty in the computation of the positive ion density. The detailed shapes of the profiles do not correlate well, nor should they if dust particles or negative ions were present in significant quantities.

Measurements in this part of the atmosphere would be greatly simplified if a slowly moving observation platform were to be developed. What is needed is a drag device such that a payload ejected

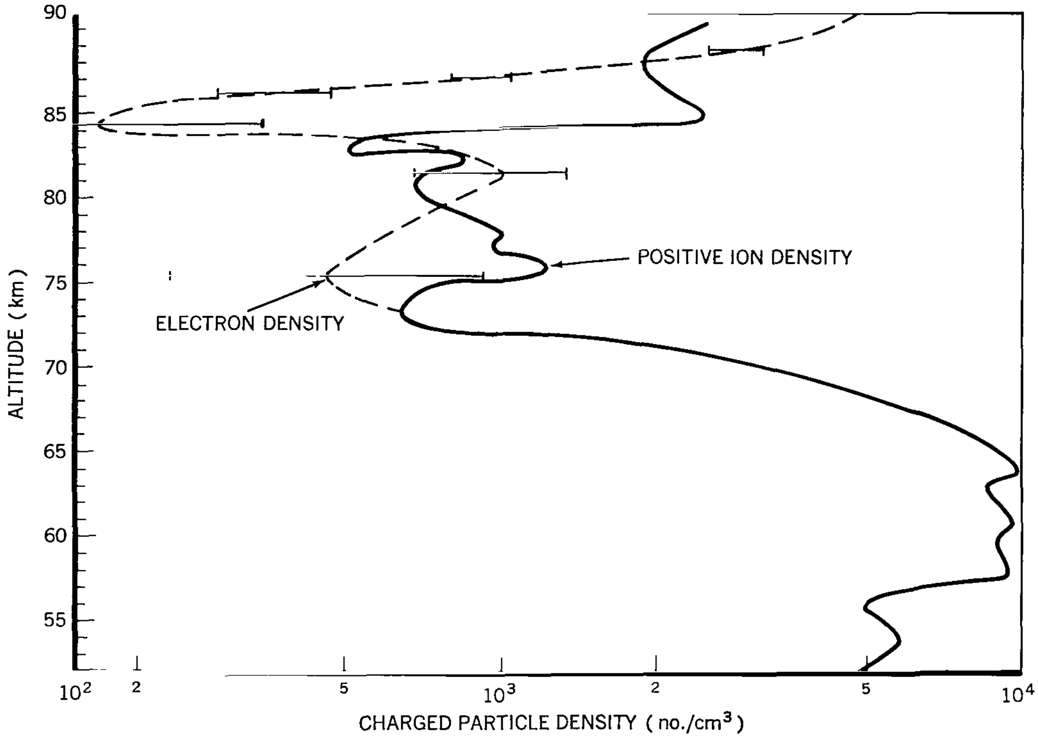

Figure 9—Charged particle densities at Wallops Island, Virginia. NASA rocket 10.74, 1630 EST, 21 December 1961 (ascent).

above 80 km would reach a terminal velocity of less than Mach 1 at 70 km. In addition to eliminating undesirable shock wave complications from experiments, such a platform would enable measurements to be made over a much longer period of time. Instrumentation response times would not have to be so short and, consequently, smaller currents could be measured. At lower altitudes the present balloon capabilities of reaching 45 km should be exploited.

Other kinds of experiments that are valid above or below this part of the atmosphere should be extended. Ion mass spectrometers are useful now only above about 90 km. A cyclotron resonance ion spectrometer that uses a superconducting magnet is being developed at present and may be useful down as low as 60 km (J. A. Kane, personal communication, 1963). The small atmospheric ions in the troposphere have never been positively identified. A simultaneous determination of the ion mass spectrum and mobility spectrum at, say, 60 km could lead by inference to ion identification at lower altitudes.

Methods now in use for determining dust concentrations and radii should be extended above balloon altitudes to establish whether dust has a significant role in the ion equilibrium problem. Electric field measurement techniques also should be extended to higher altitudes. It will be necessary to have a sensitivity such that fields considerably less than 1 volt/meter can be measured. It would be of great interest, for instance, to measure the electric field as a function of altitude between the top of a thunderstorm and the ionosphere. Such an experiment would verify conductivity measurements and would indicate the current density pattern if the field direction could be established as well.

Finally, there is a need for good cosmic ray ionization measurements above balloon altitudes. Only estimates of this quantity, based on counter results, are available at present. It will be a problem to take into account the effect of secondaries produced in structures near the experiment.

In addition to the measurements just listed, there is a need for more laboratory measurements of rate coefficients, particularly for charge exchange reactions and ion processes involving ozone.

CONCLUSIONS

It is emphasized again that the primary need at present is for reliable measurement techniques in this altitude region. Techniques involving ion or electron collection should be examined carefully before the results are interpreted in terms of geophysical quantities. Once such techniques have been developed, they should be used to establish first the normal electrical characteristics of this region during quiet conditions as defined in the introduction. The predominant processes should be established and the ion species identified. Only when this has been done will it be really possible to investigate and understand abnormal conditions that occur during solar flares or at auroral latitudes.

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